

Final report of project FA2386-10-1-4146
**Heat transfer enhancement in
small-scale devices: a collaborative
experimental/numerical approach**

Gian Paolo Beretta Pietro Poesio

November 28, 2011

Submitted to:

TAMMY K.C. LOW, Maj, USAF, Ph.D.

Deputy Director

Asian Office of Aerospace Research & Development (AOARD)

7-23-17 Roppongi, Minato-ku

Tokyo, Japan 106-0032

tammy.low@yokota.af.mil

tammy.low@us.af.mil

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 DEC 2011		2. REPORT TYPE Final		3. DATES COVERED 16-09-2010 to 15-10-2011	
4. TITLE AND SUBTITLE Heat transfer enhancement in small-scale devices: a collaborative experimental/numerical approach			5a. CONTRACT NUMBER FA23861014146		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Gian Paolo Beretta			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Universita di Brescia,via Branze 38,Brescia I-25123,Italy,IT,25123			8. PERFORMING ORGANIZATION REPORT NUMBER N/A		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD, UNIT 45002, APO, AP, 96338-5002			10. SPONSOR/MONITOR'S ACRONYM(S) AOARD		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AOARD-104146		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The aim of the project has been the analysis of spinodal decomposition of binary liquid mixtures for heat transfer enhancement in micro-devices. The work has followed two main lines and approaches: experimental investigation of heat transfer in small scale heat exchangers and numerical modeling to build a designing tool. For the first approach, the results show a significant increase of heat transfer efficiency up to 100% compared to conventional techniques, indicating that spinodal-mixture-based heat exchangers are a promising way to dissipate high specific heat fluxes in micro-electronics and small scale devices. For the second approach, we started developing a novel theoretical modeling approach that eventually will allow us to design efficient heat exchangers (based on the spinodal enhancement effect).					
15. SUBJECT TERMS thermal transport , two phase flow, Turbulent Mixing, microfluidics, spinodal decomposition					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

1 Summary

The aim of the project *Heat transfer enhancement in small-scale devices: a collaborative experimental/numerical approach* has been the analysis of spinodal decomposition of binary liquid mixtures for heat transfer enhancement in micro-devices. The project was supposed to last three years. AOARD has sponsored the first year. The project has been then taken up by EOARD for the second and third years, and is ongoing. The present document is therefore at the same time a preliminary report on the overall project and the final report on the results obtained during the first year.

The work has followed two main lines and approaches

- experimental investigation of heat transfer in small scale heat exchangers. The results (reported in Section 2) show a significant increase of heat transfer efficiency up to 100% compared to conventional techniques, indicating that spinodal-mixture-based heat exchangers are a promising way to dissipate high specific heat fluxes in micro-electronics and small scale devices;
- numerical modeling to build a designing tool. Since the currently available modeling tools would require years of computational time to complete the simulation of a practical size device, we started developing a novel theoretical modeling approach that eventually will allow us to design efficient heat exchangers (based on the spinodal enhancement effect). The results of this part are reported in Section 3.

In addition to prof. G.P. Beretta and prof. P. Poesio (faculty), the work has been done by

- dr. D. Molin, post-doc hired on the funds provided by AOARD, who worked on the numerical modeling;
- S. Farisé, Ph.-D. student hired on internal funds, who carried out the experimental work described in the following.

Co-operation with prof. N.G. Hadjiconstantinou (M.I.T.) has proven very useful in the numerical modeling of the problem.

The work done so far has been presented to three international conferences (see slides attached to this report)

1. N. Hadjiconstantinou, D. Molin, P. Poesio, and G.P. Beretta, "Multi-scale modeling of spinodal-decomposition-driven mixing", invited talk presented by D. Molin at the 3rd International Conference "Turbulent Mixing and Beyond", Trieste, Italy, 21-28 August 2011.

2. G.P. Beretta, P. Poesio, D. Molin, and N.G. Hadjiconstantinou, "Microscale heat transfer enhancement using spinodal decomposition", invited talk presented by G.P. Beretta at the Workshop on "Dynamics of Complex Fluid-Fluid Interfaces", Lorentz Center Leiden, the Netherlands, September 26-30, 2011.
3. P. Poesio, D. Molin, N. Hadjiconstantinou, and G.P. Beretta. "Macroscale approach to study heat transfer enhancement in small-scale devices", talk presented by P. Poesio at the 64th Annual Meeting of APS Division of Fluid Dynamics, Baltimore, Maryland, USA, 20-22 November 2011.

At this moment, we are working on the draft the following paper

1. S. Farisé, A. Franzoni, P. Poesio, and G.P. Beretta. "Heat transfer enhancement by spinodal decomposition in micro heat exchangers", *in preparation*.

Another paper is in preparation, based on the second part (Section 3) of this report, which however is still to be considered as work in progress, and we request that it be kept confidential.

2 Experimental Study of Heat Transfer Enhancement by Spinodal Decomposition in Micro Heat Exchangers

2.1 Introduction

With the constant rush for miniaturization, especially in electronics, and the more widespread use of integrated systems, we need technologies that allow to exchange a large amount of heat in small devices and with the highest possible efficiency.

[Tuckerman and Pease (2001)] first introduced the concept of micro channel heat sink, and since then several technologies have been developed to exchange heat more effectively.

An important distinction must be made between technologies that use a single-phase flow and those that use multiphase flows. Among these latter another distinction is between multiphase flows of a single constituent and flows of non-miscible phases.

[Tuckerman and Pease (2001)] optimized the dimensions of the channels in terms of width and height for single-phase flow of water under the constraint of maximum allowable pressure drop and substrate surface temperature. They found that single-phase water-cooling could remove up to 790 W/cm^2 . A similar optimization process was done by [Upadhye and Kandlikar (2004)]. The main problem with single-phase flow heat transfer in micro channels is the low Nusselt number obtained in laminar flow – [Shah and London (1978)] – on the order of 4.

Performance rises significantly using multi-phase technology. The study of boiling flows in a micro channel leads to much higher heat transfer coefficients due to the high heat of vaporization. [Mudawar and Bowers (1978)], [Mudawar (2001)] and [Kandlikar (2005)] showed that flow boiling can remove up to $10,000 \text{ W/cm}^2$. While flow boiling is attractive because it delivers high heat flux at the constant temperature of the phase change, it can be difficult to control due to back flow, instabilities, and local dry-out – [Kandlikar (2002)]. Usually water is the working fluid, but the problem is that the saturation temperature is higher than the operating temperature of most electronics. The proposed solution is to use refrigerants, instead of water, as working fluids since their boiling temperature is lower. Refrigerants, however, offer lower cooling capabilities due to a lower specific heat and heat of vaporization.

[Wang *et al.* (2004)], to increase the Reynolds number, proposed the adoption of small nozzles that spray water on the surface to cool. Jet array

helps to achieve uniform cooling on to the chip surface and, on the other side, a carefully located single jet can provide highly localized cooling of hot spots on chips with nonuniform heat generation.

[Betz and Attinger (2010)] investigated segmented flow as a way to enhance single-phase heat transfer with water in micro channels. Segmented flow is a periodic pattern of non-condensable bubbles and liquid slugs created by a T-junction with the injection of air in liquid filled micro channels. Experiments and optimization studies have demonstrated that segmented flow could enhance heat transfer by up to 40% in a micro channel heat sink, in comparison with single-phase flow at the same liquid flow rate. The increase in performance is significant, but the system requires the simultaneous use of both water and compressed air. This complicates the design of the heat exchanger and the tuning of the flow rate to keep the system stable and optimized.

In this study we introduce the possibility of using spinodal mixtures to generate an evenly distributed micro agitation which increases the effective diffusivity that therefore increases the heat exchange. There are, in our opinion, several appealing features that motivate the use of spinodal mixtures for heat exchange purposes. The wide variety of bi- and tri- component spinodal mixtures allows one to find the critical temperature closer to the design parameters of the device to be cooled. Moreover, since the mixture remains liquid, there are no instabilities in the flow and no pumping problems. There is also no need to re-condense gaseous phase. The composition of the mixture phases changes constantly with the variation in temperature so it is possible to obtain stirring at small scale by controlling where new domains form and grow by coalescence.

2.2 Theory

Spinodal decomposition is the spontaneous process whereby an unstable partially miscible liquid mixture relaxes toward a lower free energy (stable) equilibrium state. During this process, an initially homogeneous liquid solution of a given composition spontaneously changes from a single-phase unstable to a two-phase stable state consisting of two separated liquid phases, of different compositions, in mutual equilibrium. This is possible only if the overall Gibbs free energy of the two separated phases is lower than that of the initial single phase mixture. When an initially homogeneous liquid mixture at high temperature is cooled rapidly across the coexistence (binodal) curve into the two-phase region, it undergoes phase segregation (demixing) either by nucleation or by spinodal decomposition. Nucleation occurs when quenching takes the system in a metastable equilibrium state (between the

binodal and the spinodal curve): it is an activated process and a free energy barrier must be overcome in order to form critical nuclei that later grow and coalesce. Spinodal decomposition, instead, occurs spontaneously, without an energy barrier to overcome (the initial state is below the spinodal curve): all the concentration fluctuations are amplified regardless of their size and wavelength. If the mechanism of segregation is convection dominated, as occurs for low viscosity systems, drops move against each others under the influence of non-equilibrium capillary forces, the so-called Korteweg stresses [Poesio *et al.* (2009)]. Recently, it has been shown that this self-induced disordered bulk flow can be used to increase the heat transfer rate both in a closed configuration [Poesio *et al.* (2007)] and in small pipe flow [Gat *et al.* (2008)] and [Di Fede *et al.* (2011)]. Also numerical simulations predict a significant increase in heat transfer – [Molin and Mauri (2007)].

2.3 Experimental setup

We have used an 'upper CST' bi-component system made up by acetone and hexadecane. This mixture has been selected as it is an isopycnic system, i.e., the two phases have almost the same density and, therefore, buoyancy effects are negligible. The components are also non-toxic and can be safely used in relatively large volumes. The excess volume of this mixture has been considered negligible as it is lower than 5%. The minimal complete miscibility temperature as shown in Fig.1 is $27^{\circ}C$ and it is obtained using equal volume parts of the two components ($y_{acn} = 0.799$ in mole fraction of acetone).

Because of the shape of the spinodal curve, the heat transfer enhancement effect is maximized when the mixture is used for heating. We have developed a close loop experimental set-up that allows us to pump the mixture from a hot thermostatic reservoir to the experimental section.

Our experimental section consists of a mini heat exchanger and a Peltier cell used to set and maintain the temperature of the cold side of the exchanger throughout the test. The temperature of the cold side of the Peltier cell is kept constant by a PID computer controlled (which regulates the duty cycle of the electric power given to the cell). A thermostatic bath is used to cool the hot side of the cell. With these devices the temperature on the cold side of the Peltier cell can be kept in a range of $\pm 0.08^{\circ}C$ compared to the temperatures set by the PC. Since we used this technology (that requires electric power and some sort of cooling) and not a second fluid to cool the mixture, we have no information about the real amount of the heat exchanged. We also need a controlled temperature at the inlet of the heat exchanger that must be above $27^{\circ}C$. So we built and used a second heating thermostat, also controlled by the PC and agitated with a magnetic stirrer, to keep the temperature as

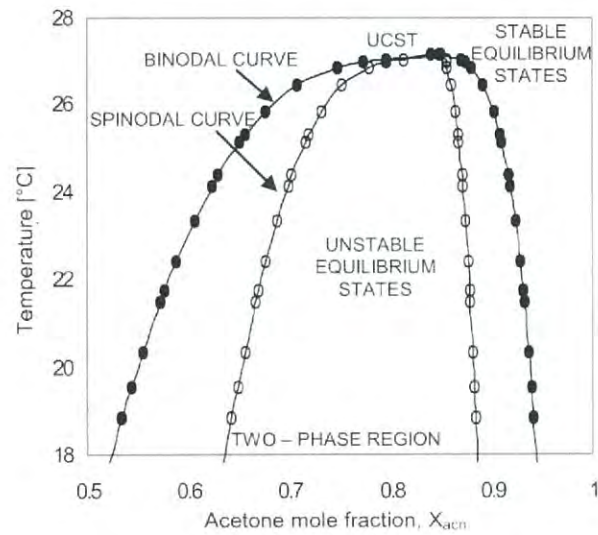


Figure 1: Miscibility-gap phase diagram Acetone-Hexadecane mixtures

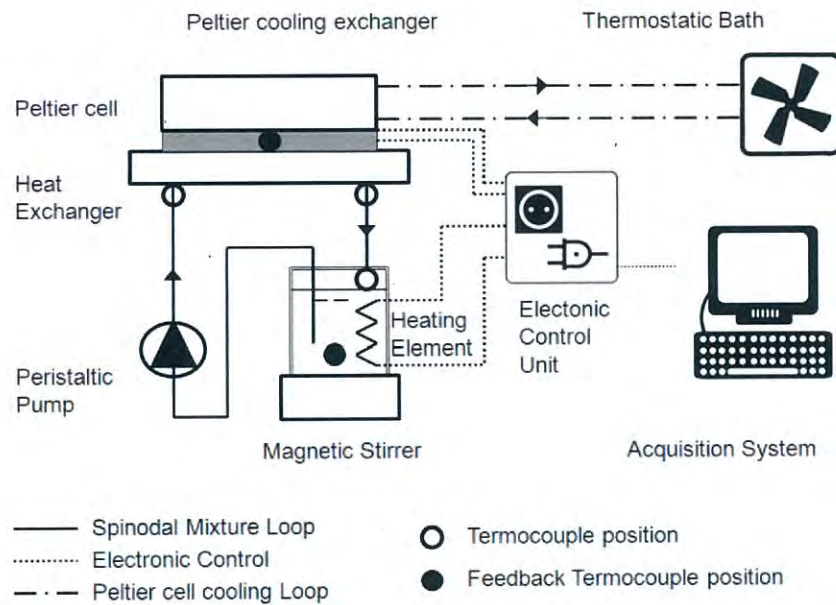


Figure 2: Sketch of the experimental set-up.

uniform as possible and to facilitate the mixing of the mixture. The inlet temperature imposed to the fluid was measured in an interval of $\pm 0.05^{\circ}\text{C}$ compared to the value set by the PC. By measuring how much heat the hot thermostatic bath gives to the mixture reservoir to keep the temperature constant we can determine how much heat has been subtracted from the hot flow. With this procedure we introduce a smaller uncertainty than measuring the heat given to an hypothetical cold flow because we need not to know the properties of the fluid, the flow rate and the position of the thermocouples. Our measurement uncertainties are only due to the voltage applied to the resistor and to the value of resistance and we are able to measure these quantities with an accuracy far greater than temperature and flow rate.

Our experiment has been done on 3 different types of heat exchangers.

The first and most simple is the single channel (Fig.3A): we cut a channel (section of $0.7\times 0.7\text{mm}$ and 38mm long) in a piece of copper. The top and the bottom of the channel are sealed with a thin glass to record with a high speed camera the test section. We placed a Peltier cell on each side of the channel to finely control the temperature and to be sure to have no gradient at all. A gradient would perturb the flow of the mixture and complicates the mechanics of heat transfer.

We used this heat exchanger for visualization and validation purposes: the exchange area is small so the difference in heat exchange is small, too. Therefore the experimental uncertainty is greater than that obtained using the other heat exchangers.

Despite the single channel is very useful to understand the mechanism of the spinodal decomposition its industrial applications are limited. We have built a second heat exchanger with 9 parallel channels (0.7mm wide 1.5mm tall and 72mm long). As the previous one this also has a glass top to view the flow pattern of the mixture during cooling. This set-up requires just a single Peltier cell placed behind the array of channels as shown in (Fig.3B).

The third heat exchanger (Fig.3C) is something very similar to the real heat sinks used to cool CPU. It is a compact multi-channel array (14 channel) with a U shape. This too is sealed with a glass and cooled with a Peltier cell behind the channels.

We used a total of 5 (6 in the single channel configuration) thermocouples: the first is placed in the mixture reservoir to constantly monitor the temperature of the hot mixture and as a feedback for the PID controller of the hot thermostatic bath; the second and the third are placed at the inlet and at the outlet of the heat exchanger; the forth is placed at the end of the outflow hose just before the hot reservoir to verify the heat balance; the last one (or the last two in the single channel set-up) is placed on the cold side of the Peltier cell to set and monitor the cold side temperature and as a

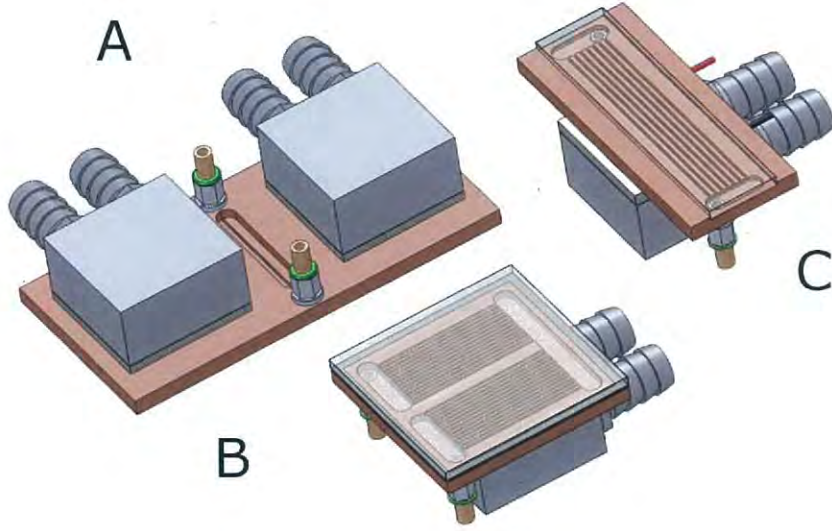


Figure 3: The three heat exchangers we tested in our experimental setup.

feedback for the Peltier cell PID controller.

All thermocouples are type T, fabricated in our lab by wires coming from the same hank; each thermocouple is calibrated using a cold bath (0°C , ice/water), we could verify the resulting uncertainty to be in the range of $\pm 0.2^{\circ}\text{C}$. In addition, each measure presented in this study has been obtained using the thermocouples differentially so that the uncertainty of measurement is reduced to $\pm 0.08^{\circ}\text{C}$.

2.4 Experimental procedure

For each heat exchanger tests were carried out with bi-distilled water (for validation purpose), pure acetone, pure hexadecane, and the spinodal mixture. The procedure is as follows:

- we switch on the thermostatic bath to cool the Peltier cell;
- we use the maximum flow rate available (30ml/min) to ensure the best filling of the channels array;
- the flow rate is reduced to 10% of the maximum (3ml/min);

- the temperature of the Peltier cell is brought to the desired value for the run;
- keeping fixed the temperature of the Peltier cell the heated reservoir temperature is increased to the desired value;
- we wait 5 minutes to reach a stable temperature condition and then we start the data acquisition;
- data for each flow rate are acquired for 5 minutes, then the flow rate is increased by 5%;
- the previous step is repeated until the maximum flow rate achievable in our test facility is reached;
- the temperature of the cold side of the heat exchanger is reduced and all the steps are repeated for the new temperature;
- the system is cleaned with solvent and dried with an air flow until complete drying.

The previous steps are repeated for each of the 4 fluids used on each heat exchanger.

2.5 Set-up validation

2.5.1 Heated reservoir maximum power

The first parameter that we need to know during the validation of our system is the maximum electric power converted via Joule effect into heat power by the resistance of the heated reservoir. We need to know this exact value because we do not record step by step the electrical power value but only the duty cycle value, $DC(t)$, from which we estimate the converted power:

$$\dot{Q}_{el}(t) = DC(t)\dot{Q}_{el}^{Max}. \quad (1)$$

To evaluate this value we recorded a test section with the peristaltic pump off. By doing so and assuming that all the electrical power is converted into the heated bath, we can compute its value with this formula:

$$\dot{Q}_{el}^{Max} = mc_p \frac{dT}{dt}. \quad (2)$$

Fig. 4 shows the trend of the temperature of the hot thermostatic bath during the test. It is, as expected, almost linear because the properties of water in this temperature range are, with good approximation, constant. We used 200ml of bi-distilled water and the frequency of the acquisition was 3Hz.

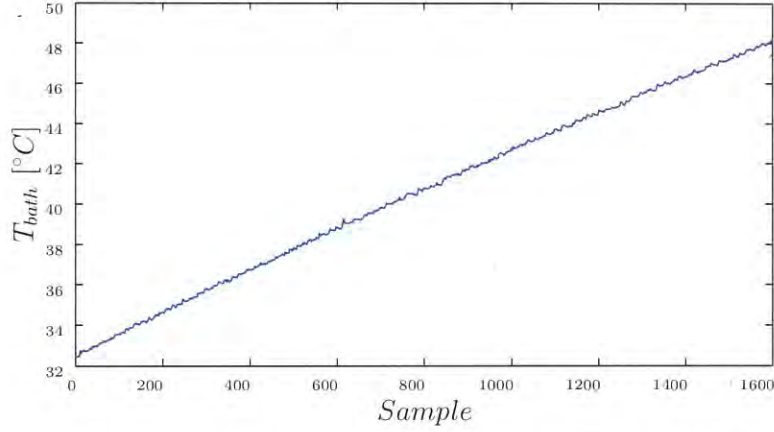


Figure 4: T_{bath} variation during the validation test.

2.5.2 Power balance validation

As already explained, to demonstrate the heat transfer enhancement effect by the spinodal decomposition of the mixture we measure the electrical power sent to the resistor in the magnetically stirred thermostat.

This is necessary because we do not know the real thermo-physical properties of the mixture and moreover we are sure that in our temperature range they are variable.

Therefore, we want to demonstrate that all the electrical power converted in heat by the resistor is exchanged across the test section. The power balance for our closed system has four contributions

$$\dot{Q}_{inletpipe}^{\rightarrow} + \dot{Q}_{testsection}^{\rightarrow} + \dot{Q}_{outletpipe}^{\rightarrow} = \dot{Q}_{Jouleresistor}^{\leftarrow} \quad (3)$$

$\dot{Q}_{inletpipe}^{\rightarrow}$ is the heat lost by the inlet pipe between the hot thermostatic reservoir and the test section;

$\dot{Q}_{testsection}^{\rightarrow}$ is the heat exchanged in the test section;

$\dot{Q}_{outletpipe}^{\rightarrow}$ is the heat exchanged in the outlet pipe, between the test section and the hot thermostatic bath;

$\dot{Q}_{Jouleresistor}^{\leftarrow}$ is the electrical power converted in heat by the resistor.

Fig. 2.5.2.a shows the various contributions for the U-shape multi-channel heat exchanger with:

- fluid = water;
- $T_{bath} = 35^{\circ}\text{C}$;

- $T_{Cu}=25^{\circ}\text{C}$;

Fig. 2.5.2.b shows that our hypothesis is quite good and our system can actually be validated since the difference between the electrical power and the heat exchanged is always within a 5%. It is possible to see that the error is greater for the lower fluid velocities for two main reasons: first of all because the heat exchanged is smaller so the percentage error is greater; secondly it is caused by the imperfect insulation of the hot reservoir. We prefer to trust the data above 10 ml/min, but we will report all available data for the sake of completeness. After validating our system using water (it is the most stable fluid in the temperature range involved) we checked our assumption with the other pure fluids.

2.5.3 Single channel heat exchanger validation

The single-channel exchanger is useful for our analysis because the theory behind the heat transfer in a square channel is well known, so comparing our results with the theoretical ones, we obtain a good feedback about the accuracy of our work.

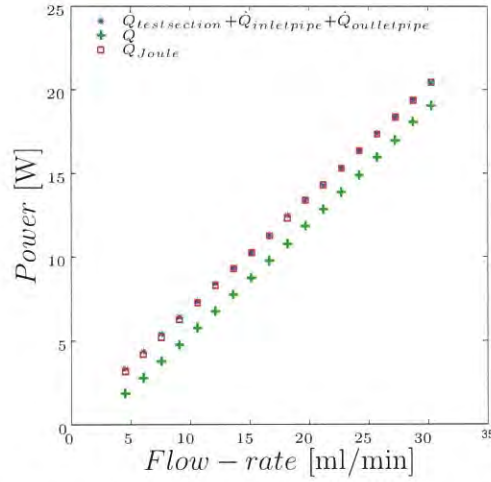
The main problem we had in the data evaluation is the correct estimation of the inner exchange area of the channel. Due to geometry and sealing problems we could not put the thermocouples at the actual input and output of the channel, but we put them just outside the heat exchanger. This implies that the measured temperatures are not referred to the channel ends, but to the exchanger ones. Thus, the exchange area is greater than the channel area. Being difficult to measure directly, we measured the actual exchange area via software by using a 3D model.

The experimental data are consistent with the area measured this way, therefore, we used it for all subsequent calculations.

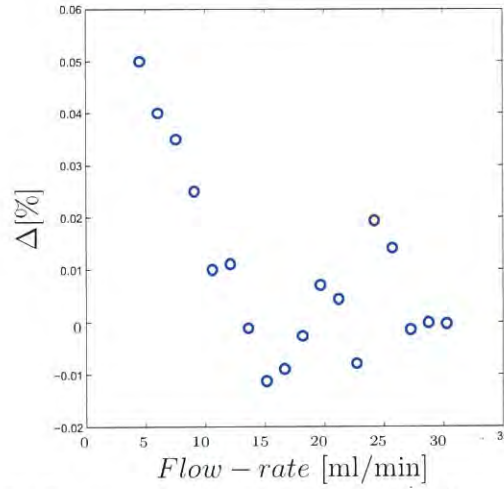
Fig. 7 shows the results for the Nusselt number, the points refer to the experimental data, while the line refers to the theoretical correlation.

2.6 Experimental Results

To obtain the heat exchanged during phase transition, several experiments were conducted following the experimental procedure outlined in Section 2.4. The experimental results correspond to various flow rates of the solvent system in the heat exchangers at different inlet temperatures and wall temperatures. The experiments were conducted with pure fluids and with a mixture of critical composition (critical molar composition is $y_c = 0.799$ where $y = y_{acn}$ is the mole fraction of acetone and, of course, $1 - y = y_{hex}$ that of hexadecane) and with pure fluids.



(a) Power balance made in a water test with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=25^{\circ}\text{C}$.



(b) Percentage difference $\Delta = (\dot{Q}_{Joule} - \dot{Q}_{testsection} - \dot{Q}_{inletpipe} - \dot{Q}_{outletpipe}) / \dot{Q}_{Joule}$.

Figure 5: Power balance validation

2.6.1 Single channel heat exchanger

Fig. 7 shows the results for the Nusselt number, the point refer to the experimental data, while the line refers to the theoretical correlation. Even if the

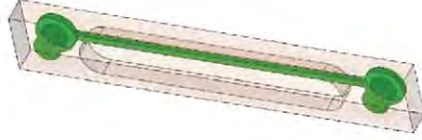


Figure 6: Total exchange area in our mini channel heat exchanger.

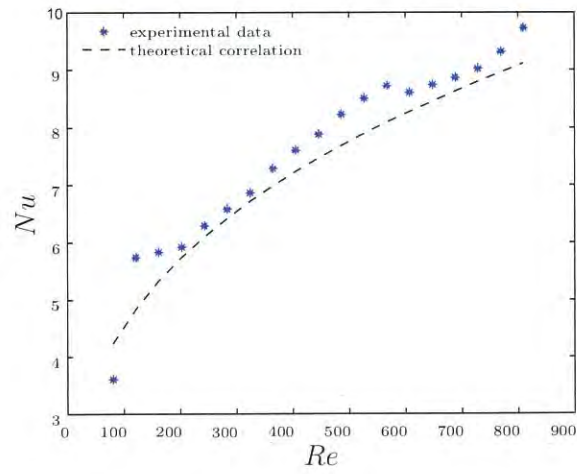


Figure 7: Comparison between theoretical and experimental Nusselt numbers in a single-channel test with water, $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$.

Reynolds numbers are always lower than the critical one for the transition from laminar to turbulent, we see that the correlation for laminar flows does not work well. This probably due to the inlet and the outlet hoses being perpendicular to the channel, causing an instability in the first part of the channel which maybe changes the motion from the expected laminar condition. The effect seems more pronounced for acetone, so much that while water (Fig. 7) and hexadecane (Fig. 9) we find reasonable agreement with laminar correlation for simultaneously developing laminar flow at constant wall temperature (Stephan), for acetone the agreement is reasonable only if we compare with the turbulent Petukhov-Gnielinski correlation (Fig. 8)

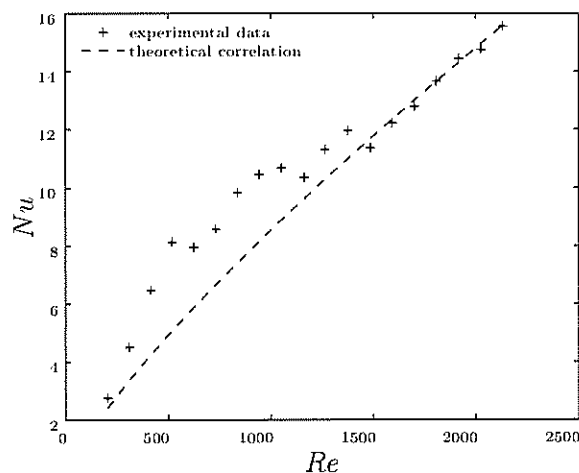


Figure 8: Comparison between theoretical and experimental Nusselt numbers in a single-channel with pure acetone with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$.

The main result for this test section is presented in Fig. 10, where we plot the electrical power absorbed by the resistor during a test made with all our fluids with fixed values of $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=25^{\circ}\text{C}$. These results are interesting because during this test the temperature in the channel does not go below the UCST value, so there is no decomposition; without decomposition the properties of the mixture are ideally related only to the properties of its constituents. This test demonstrates that the power absorbed with pure acetone, pure hexadecane, and the mixture with critical composition is almost the same.

Then we imposed a lower temperature on the heat exchanger ($T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$) and we calculated the theoretical Nusselt number for laminar flow using the thermo-physical properties computed with the formulas valid

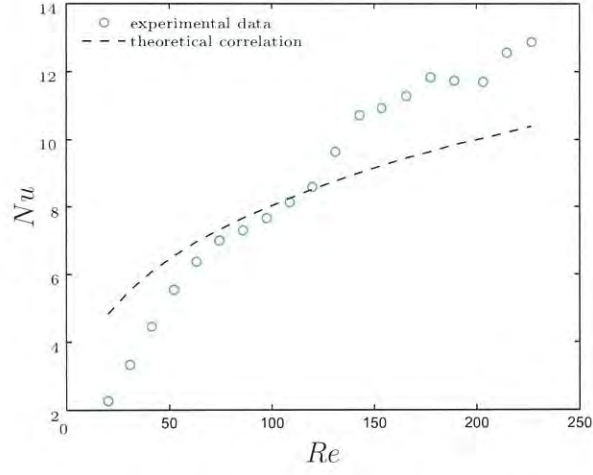


Figure 9: Comparison between theoretical and experimental Nusselt numbers in a single-channel with pure hexadecane with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$.

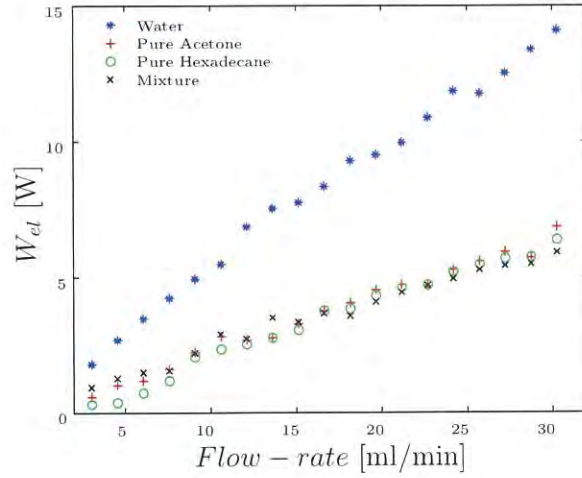


Figure 10: Absorbed electrical power with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=25^{\circ}\text{C}$.

above the UCST. Fig. 11 shows that the experimental Nusselt number is almost a factor of 2 higher than theoretical correlation would predict. We take this as a demonstration of the enhancement due to micro-agitation induced by spinodal decomposition.

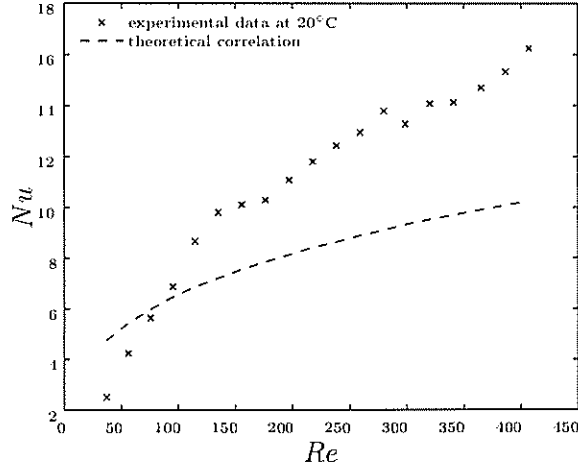


Figure 11: Comparison between theoretical and experimental Nusselt numbers in a single-channel with mixture with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$. Here the quench is deep enough that spinodal decomposition induces a heat transfer enhancement of almost a factor of 2.

2.6.2 Multi-channel heat exchangers

As for the single channel, we tested the multichannel exchangers with the same two quench temperatures of 25°C and 20°C . With 25°C , our visualization, do not show spinodal decomposition; with 20°C , instead, the quench is deep enough that we do observe vigorous spinodal decomposition in the section. Figs. 12 to 15 show the heat exchanged by the pure fluids and the critical mixture.

To evaluate the enhancement effect, we compute the Ideal Augmentation Factor defined in [Di Fede *et al.* (2011)]:

$$AF_{id} = \frac{\overline{Q}_{Joule} - \overline{Q}_{mix}}{\overline{Q}_{mix}} \quad (4)$$

Where \overline{Q}_{Joule} is the heat exchanged measured by the hot reservoir feedback information during our experiments and \overline{Q}_{mix} is the heat that the mixture

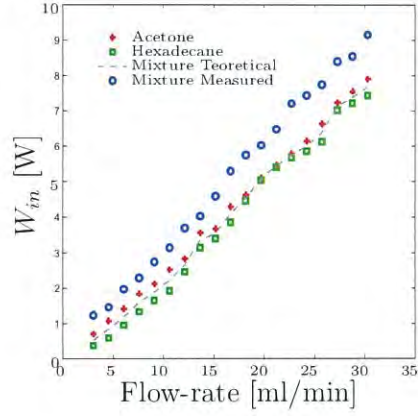


Figure 12: Electric power absorbed by the parallel heat exchanger with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=25^{\circ}\text{C}$.

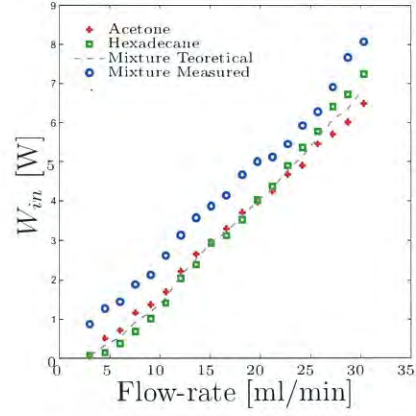


Figure 13: Electric power absorbed for the U-shape heat exchanger with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=25^{\circ}\text{C}$.

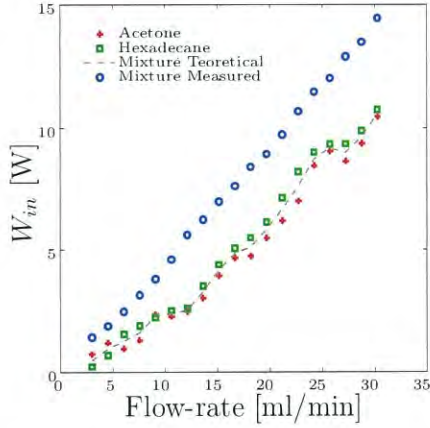


Figure 14: Electric power absorbed by the parallel heat exchanger with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$.

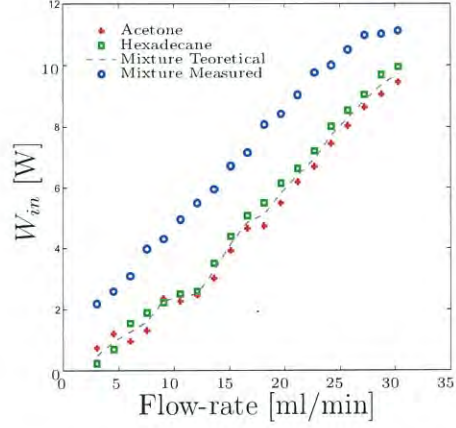


Figure 15: Electric power absorbed for the U-shape heat exchanger with $T_{bath}=35^{\circ}\text{C}$ and $T_{Cu}=20^{\circ}\text{C}$.

would exchange if the Cp_{mix} is the mean between $Cp_{acetone}$ and $Cp_{hexadecane}$.

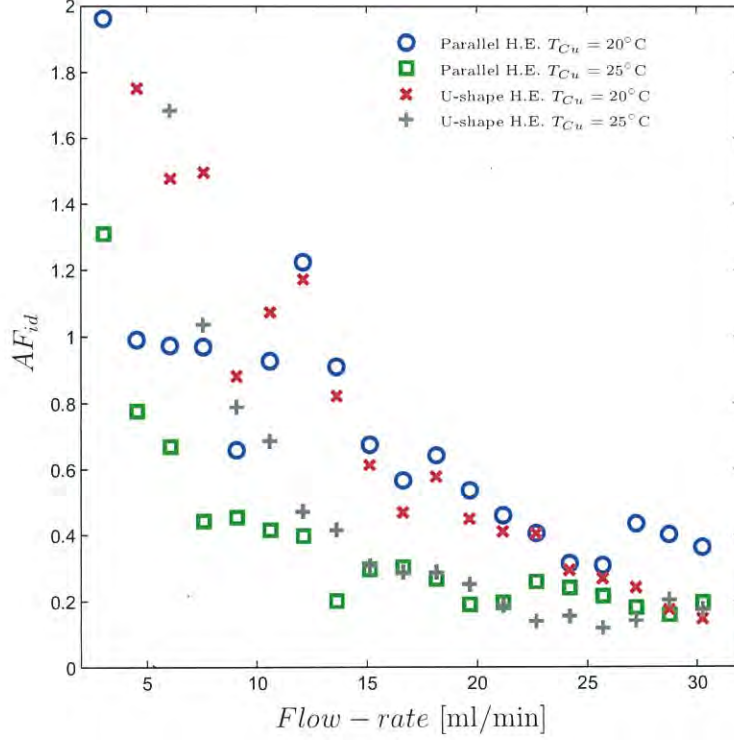


Figure 16: Heat-transfer Augmentation factor as defined by [Di Fede *et al.* (2011)], computed from the data in Figs. 12 to 15.

As we can see in Fig. 16 the performance increase is greater at the lower flow rate. This is because there is a sort of summation of the effects: the more is the heat exchanged because of the increase of flow rate the less is the heat exchanged due to the spinodal decomposition induced convection.

2.6.3 Spinodal decomposition visualization

As we said in the previous section the greater is the thermal gradient the more the heat exchange is increased. In Fig. 17 we can notice how the induced convection increase with the quenching depth.

Figure 17 represents the same piece of channel with constant flow rate (flow rate was set to the lower value possible for our set-up -1.5ml/min- to

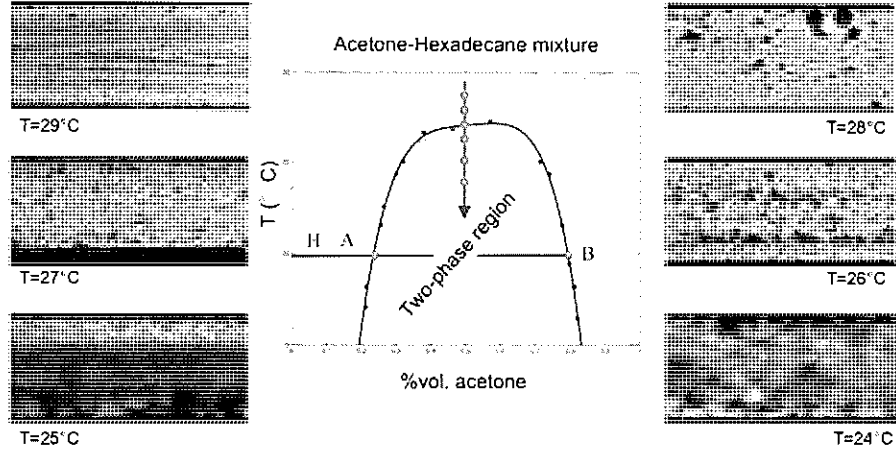


Figure 17: Quench of acetone-hexadecane mixture.

take better pictures) at different T_{Cu} temperatures. We can see that there are two types of flow. At higher temperatures (above the spinodal region) we see the presence of relatively large bubbles; these are probably due to the fact that a little decomposition can be induced by shear in pipes. At lower temperatures (under the spinodal curve) there is the formation in situ of a large number of micro-droplets that induce convective motion because of the difference in composition of the two phases. Both effects increase the heat transfer, but the second in much more vigorous way.

2.7 Conclusions

We have reported experimental data on heat transfer enhancement due to spinodal decomposition in single and multi channel heat exchangers. The enhancement increases with small channels and with low flow rate. This is a good point because these are usually the worst condition due to the small Nu numbers. In the future we are going to decrease as much as possible the size of the channel to obtain higher enhancement factors. Decomposition under temperature gradient is going to be studied too, because we think that a little gradient can increase the induced convection.